Microwave rf hazards

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Introduction

An earlier article [1] introduced the general topic of the safety or otherwise of rf sources such as transmitters. It was pointed out that a hazard could exist if parts of the body absorbed sufficiently large amounts of rf energy to cause overheating. By the very nature of the hazard, it is impossible to specify any absolutely safe or unsafe level of rf power with any precision. However, the main conclusion of the article referred to (as well as others of a similar nature) is that with typical amateur hf and vhf stations where the antennas are mounted well above ground level, the measured rf levels at points of close access generally are at least 100-fold down and up to several orders of magnitude lower than the standard "safe" level of 10mW/cm² even when using full legal power. In these practical cases, therefore, there clearly are few problems, and even arguments about what constitutes a "safe" level become somewhat academic.

However, the rf level associated with even relatively low-power transmitters can increase to an unacceptably high level as one gets close to them, and the article emphasized the care that must be taken in testing equipment on the bench with covers removed or with unscreened dummy loads. Handy-talkies, especially those using "rubber-duck" antennas, may represent a hazard if their power output exceeds a few watts.

While the same basic principles regarding rf hazards apply also in the microwave area, there are significant differences compared with lower frequencies. For example, microwave equipment is more often operated near ground level for various reasons; there is more experimental development of equipment; and, for a given transmitter power, the rf power density close to the antenna will tend to increase with frequency. For these and other considerations, the topic of rf hazards at microwaves is best dealt with separately and in perhaps more detail than at hf and vhf.

Anyone involved in safety matters, whatever the area, will be well aware how difficult it is to maintain a sense of perspective. The illogicality of many safety procedures bears testimony to this. It is all too easy to "play safe" and lay down over-restrictive rules which, at best, simply inhibit activity and, at worst, become discredited and then ignored. The objective of this article is to attempt to develop a code of practice appropriate for day-by-day use by amateurs which will reduce to a minimum the risk involved to operators and bystanders. This code is summarized below. It is followed by an outline of the nature of the hazard, and the technical background employed in developing the code.

Safe generating practices with microwave equipment

It is easy to demonstrate that the maximum rf power density associated with amateur microwave equipment will almost always be significantly lower than 10mW/cm² at even a short distance away from the antenna. Indeed, it would be rather difficult to produce a practical system in which this level was exceeded at any distance. In any case, equipment parameters can be specified to ensure that it does not. However, where the effective aperture of a system carrying rf is small, eg the open end of waveguide and in feeds for dishes, the density can be very high and at a hazardous level. Thus for practical systems amateur microwave equipment will almost always be safe at almost any distance outside the structure of the antenna, and almost always will present a hazard within the structure, eg between the feed and a dish or inside a horn antenna. Therefore the only real risk is to operators and others who have access within a very short distance of these components.

The following is an attempt to define a code of practice for the safe handling of microwave equipment in an amateur context.

1. It must be recognized that a potential hazard exists wherever equipment having a small effective aperture—such as the open end of waveguide and coaxial cable, horn and rod feeds—carries rf above a level ranging from 1mW at 24GHz to a few hundred milliwatts at 1·3GHz. As a guide, the input power should not exceed 2·5mW/cm² of area of the aperture if the maximum rf power density is not to exceed 10mW/cm².
2. For these small apertures, the maximum rf density is reached at a distance typically λ/10 to 1λ from the aperture, and falls rapidly by a factor of 100 at a distance of 1–10λ: the potential hazard therefore exists over a short range only.
3. When working in close proximity to equipment, it is highly desirable to reduce power levels to below those given in **1**. Where this is not possible, it is essential to dissipate the power in a screened load.
4. One golden rule should be to ensure *no* rf is present before looking down waveguide, because of the special vulnerability of the eye.
5. With high-power equipment, a hazard may exist through leakage of rf from loosely-coupled connectors and waveguide flanges, and from the coupled output of directional couplers. The power *reflected* from surfaces may exceed a safe level. Clearly, good practice demands care and discipline—and foresight.
6. It is strongly recommended that the rf power fed to a paraboloidal dish reflector should not exceed 2·5mW of its projected area. This will ensure that the rf power density will nowhere exceed 10mW/cm² except for the region between the feed and the dish. This limit corresponds to approximately 2W for a dish 0·3m in diameter, and 80W for a dish 2m in diameter, and therefore is unlikely to present any practical limitations to the design of equipment.
7. If the dish is fed using the Cassegrain system, then it is recommended that the power delivered to the antenna should not exceed 25mW/cm² of the area of the *sub-reflector*, or 2·5mW of that of the main reflector, whichever is the smaller value. In this case the leakage of rf around the sub-reflector should be less than 10mW/cm².
8. Care must be taken to ensure that the feed is placed in the correct position at the focus of the dish. If further from the dish than this optimum value, an image of the feed will be produced at a finite distance. The rf power density at this point may approach that at the feed and therefore be at an unsafe level. It is clearly good practice to align antennas using powers at the milliwatt levels as given in **1**.
9. If the power to an antenna is limited as in **5** and **6**, then the rf power density will be at a safe level everywhere other than in the region between the feed and the dish. As the power density at the feed may be very high, it is essential to limit access to this region, especially by those unfamiliar with the hazard. This can be achieved either by restricting access to the site or by raising the antenna so that its height at the centre exceeds 3m.
10. In the case of horn antennas it is recommended that the power level should be limited to 2·5mW/cm² of the area of the aperture. For most horns this is equivalent to $2 \times l^2$ where l is the length of the longest side of the aperture.
11. Higher power densities can of course be tolerated provided the operator of the equipment ensures that people cannot have access to these regions.

Nature of the hazard

As was pointed out in [1], the hazard associated with high rf levels is completely unconnected with radiation hazards associated with γ- or X-rays for example. It is simply that of heating of parts of the body following absorption of the radiation, and therefore is similar to the hazard of over-exposure to the sun or sitting too near a fire. The effectiveness of this form of heating is well demonstrated by the microwave ovens with which amateurs share the 2·3GHz band. The main factor affecting the degree of hazard is the power density of the rf intercepted by the body. Convenient units are either watts per square metre or milliwatts per square centimetre. A second factor is the frequency of radiation, which affects the proportion of incident radiation absorbed, the site of its absorption and the power density developed by a transmitter of a given output power. These factors will be discussed below.

The effect of controlled heating can be positively beneficial, as in diathermy treatment, but large doses or even an accumulation of doses can lead to permanent damage to body tissues without a person necessarily being aware at the time that this damage is being done. One of the more vulnerable organs is the eye: the viscous fluid within the eye is affected by heat in much the same way as the white of an egg, which is transparent at room temperature but becomes opaque when warmed. In the eye, as in the egg, the process is irreversible.

Physiological characteristics also affect the degree of hazard. Thus at lower frequencies the intestines tend to be vulnerable because this is the region in which heat is generated and, being not particularly well-endowed with nerves, the effect is not immediately felt. The eye is also vulnerable because it has no bloodstream to assist in dissipating any heat that may be generated, although the same effect will also be observed at extremities such as the fingers. The effect of frequency of the radiation is quite critical. Below about 150MHz the human body tends to become transparent to rf radiation and therefore there is no real problem. At vhf the radiation penetrates

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deeply into the body, and the more vulnerable parts are the internal organs. At 1–10GHz the energy tends to be dissipated in the skin and the organs immediately below the surface: at high power densities there is a sensation of warmth. Above 10GHz energy is absorbed in the surface layers, although it appears that a high proportion of the incident rf will be reflected.

There is a further effect which relates the absorption with the size of the organ and the wavelength of radiation. Radiation of a given density having a wavelength of 23cm, for example, will have less effect on the eyes which have dimensions of one or two centimetres than radiation of wavelength of 3cm, ie 10GHz.

Another potential influence of frequency is that of affecting the rf power densities likely to be produced in practice. For a transmitter of given power, the radiation density developed is roughly proportional to frequency. However, the amount of power that can be generated tends to fall by a corresponding amount, and thereby balancing the risk of a hazard.

Frequency is also important in the way it influences the design and use of the equipment. At lower frequencies, antennas have relatively low gain and coaxial cables have low loss: this means that antennas can readily be mounted high, usually tens of feet above ground level. At high microwave frequencies, however, there is a tendency to operate equipment near ground level. This is because antennas are so directive as to need some optical method for alignment, and cable losses so high that the antennas need to be mounted on the transmitters. These factors conspire to favour the antenna being mounted at head height, which is the least desirable from a safety point of view. Despite the complexity of the overall situation, nevertheless the majority of problems can be covered simply by specifying a maximum power level to which parts of the body should be exposed, and this is described in the following sections.

Specification of "safe" rf power densities

The previous section describes several of the factors affecting the degree of hazard. It is therefore not surprising that while all authorities agree that exposure to radiation having a density of more than 100mW/cm² is likely to be hazardous unless special clothing is worn, there is room for discussion on what constitutes a "safe" level. The Home Office and the Medical Research Council recommend a maximum density *for continuous exposure* of 10mW/cm². This figure implies some extra margin of safety in an amateur context, since exposure is unlikely to be classifiable as "continuous" or cover other than a small part of the body at one time. It is to be noted that some standards have allowed a maximum of 100mW/cm² for periods up to 6min of exposure.

On the other hand, it is to be recognized that much amateur equipment can be of an experimental nature and not necessarily fully instrumented. Unexpectedly high radiation densities due to a power amplifier starting to oscillate, or to poor design of antennas, suggest a need for added caution. It would therefore seem wise initially to adopt a temporary arbitrary lower maximum power density during initial experimentation—possibly 1mW/cm²—until the equipment is properly set up.

Table 1. Maximum power for 10mW/cm² not to be exceeded at open end of waveguide

Frequency (GHz)	Waveguide No	Internal dimensions (cm)	Maximum power (mW)
1·3	6	16·510 by 8·255	340
2·3	8	10·922 by 5·461	150
2·3	9A	8·636 by 4·318	93
3·4	10	7·216 by 3·403	61
5·7	12	4·755 by 2·215	26
5·7	14	3·485 by 1·580	14
10	16	2·286 by 1·016	5·8
24	20	1·067 by 0·432	1·2

Characteristics of the radiation pattern

It is useful to consider first radiators such as the open end of waveguides or the horn antenna, and then to move on to paraboloidal dish antennas. It can be shown that the pattern of radiation across the aperture is not uniform across a waveguide or horn in the H-plane, but follows a sine wave. Thus while the mean power across the aperture is simply P/A, where P is the power and A the area of the aperture, the peak power density is nearly four times this value, ie approximately 4P/A. The use of the latter value introduces a small safety factor which is increased by the use of the physical aperture for A rather than the electrical aperture.

The maximum power density is observed along the axis of the radiator, and falls to either side. In the case of paraboloidal dish antennas, a similar pattern is observed; the feed being designed so as to reduce the power density at the edge of the dish by typically 10dB. The maximum density is not, as perhaps would be imagined, at the aperture, but at a distance further from the dish given by $0.2D^2/\lambda$, where D is the diameter of the reflector in the same units as λ. This relationship is equivalent to approximately $A/4\lambda$, which value can be used as a convenient guide with other shapes of aperture.

Between the radiator and the point of maximum power density, the density varies in a sinusoidal manner at a level a few decibels lower than the peak value. Beyond the peak the density falls rapidly and reaches a value 20dB down at a distance given by $2D^2/\lambda$ (or $2{\cdot}5A/\lambda$), and thereafter falls at a rate set by the inverse square law. The overall pattern of power density normalized in terms of D^2/λ is shown in Fig 1 with reference to a peak density of 10mW/cm².

Open ended waveguide

As will become apparent, the radiation from the open end of waveguide represents probably the greatest risk in practice. It is compounded by the almost irresistible urge many people have to look into it.

The size of waveguide used at a particular frequency is set within fairly narrow limits: the broad width usually lies between 0·6 and 0·95λ, and the height usually is approximately 0·45λ. The value of A therefore is typically

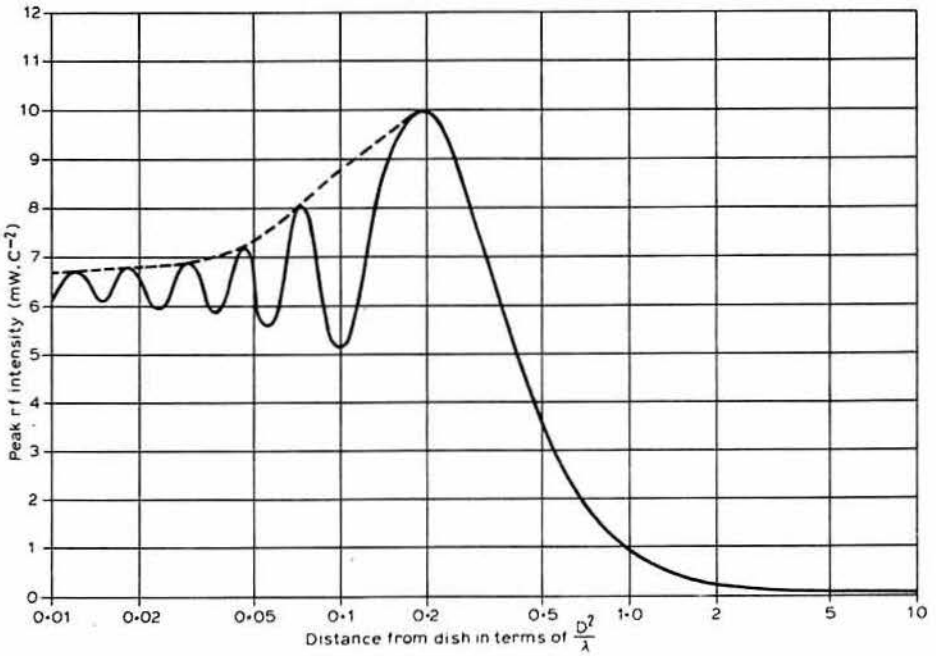

Fig 1. Peak rf density relative to 10mW/cm² as a function of distance from dish expressed in terms of D^2/λ, where D is the diameter of the dish and λ the wavelength of radiation, both expressed in the same units

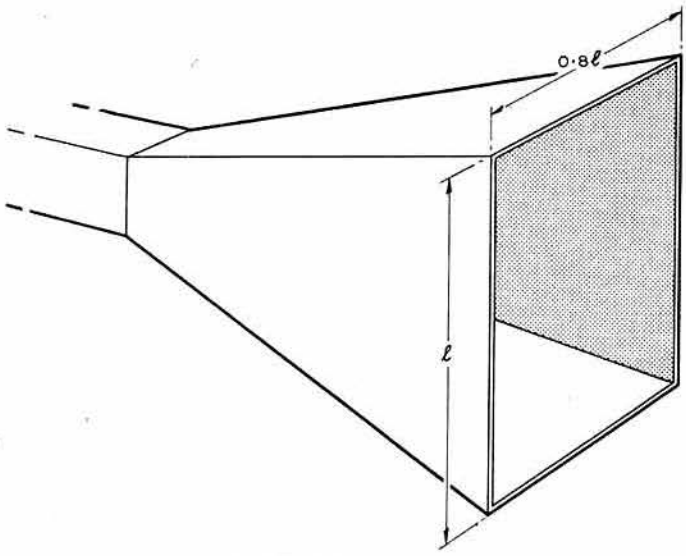

Fig 2. Typical horn antenna

$0{\cdot}27\lambda^2$—$0{\cdot}43\lambda^2$. The maximum power P that can be fed to the waveguide without exceeding 10mW/cm² peak rf power density is therefore $0{\cdot}67\lambda^2$—$1{\cdot}07\lambda^2$, where P is in milliwatts and λ in centimetres. The maximum density is measured at a distance $0{\cdot}13\lambda$—$0{\cdot}21\lambda$ in front of the aperture, and drops by a factor of 100 at a distance of $1{\cdot}35\lambda$—$2{\cdot}15\lambda$. The maximum powers that should be applied to typical waveguides at frequencies of amateur interest so as not to exceed 10mW/cm² are given in Table 1: they are seen to be at relatively low levels. This implies that in most cases the output of most transmitters constitutes a real hazard and therefore the waveguide should always be safely terminated in a screened load where access is permitted.

As an example, the maximum radiation density from a 100mW 10GHz transmitter based on WG16 reaches a peak value of 170mW/cm² at a distance of approximately 5mm in front of the waveguide aperture. However, this falls to 1·7mW/cm² at a distance of approximately 40mm from the waveguide aperture.

Horn antennas

In the form generally used by amateurs, Fig 2, horn antennas consist of a length of waveguide which is flared in both directions to produce an aperture having an aspect ratio of typically 0·8:1. The radiation density within the horn falls from a relatively high value at the throat of the horn to a low value at the aperture. For the peak radiation density anywhere *outside* the antenna not to exceed 10mW/cm², the power in milliwatts fed to the antenna should not exceed $2 \times l^2$ where l is the length of the longer side in centimetres. Because of their relatively large physical size relative to their gain, horn antennas tend to be used at frequencies of 10GHz and above. At that frequency a reasonably large horn would have an aperture of 30 by 24cm. The maximum power that could be fed to this antenna without exceeding 10mW/cm² at the aperture would be 1·8W, a very considerable power at that frequency.

The power density at the aperture is given by $5P/l^2$. For a medium size (10GHz) transmitter of output power 100mW, the density is only 0·6mW/cm², ie at a very safe level. The corresponding density at the throat increases to 170mW/cm², but this region is not easily accessible other than by deliberate action. For this reason, and the fact that they cannot be misaligned, horns tend to be a particularly safe form of antenna to use.

A feature of note is that as the aperture of the horn is increased so the gain of the antenna increases, and therefore the effective radiated power is raised. At the same time, the larger the aperture the lower the power density at the aperture, and therefore the safer the equipment becomes. We therefore have the perhaps surprising situation that, for a given transmitter output, it is possible to have the situation that the higher the radiated power the safer the equipment can become.

Paraboloidal dish antennas

This is the most popular form of microwave antenna. It consists of a paraboloidal reflector to which rf is fed by some form of feed placed at its focus. There are two areas of importance, which can be dealt with separately: the hazard associated with the radiation reflected by the dish and which will be at a maximum at some distance outside its focus; and the hazard associated with the region between the feed and the dish.

Reflected power. The pattern of radiation from a dish reflector is approximately a cone. This has an initial diameter equal to that of the dish, which increases with distance from the dish according to the beamwidth of the antenna. The radiation density across this cone is at a maximum at its centre, ie along the axis of the dish, and is designed to fall typically by about 10dB at the edge of the cone. Along the axis the peak radiation density is found near the limit of the near field, ie at a distance $0{\cdot}2D^2/\lambda$ from the dish, where D and λ respectively are the diameter of the dish and the wavelength of the rf expressed in the same units. Values for frequencies of amateur interest as a function of antenna size are shown in Fig 3.

The peak radiation density in most cases will be observed at distances of 1 to 10m from the dish, ie well beyond the focus. The peak radiation density corresponding to this reflected power is again given by the value 4P/A, where P is input power in milliwatts and A is the projected area of the dish in square centimetres. For this peak density not to exceed 10mW/cm², the maximum power should not exceed the values:

$P_{max} = 2D^2$ where P is in milliwatts, D (diameter) in centimetres

$P_{max} = 20D^2$ where P is in watts and D in metres.

This relationship, together with that for a maximum density of 1mW/cm², is shown as a function of dish diameter in Fig 4, with regions designated as "most safe", "safe" and "unsafe". Thus, for example, if a 1·5m dish is available, provided that the power fed to it does not exceed 44W, then nowhere outside the antenna structure will the power density be greater than 10mW/cm². It should be noted that this relationship is independent of frequency. This means in practice that a high degree of safe operation can be "built-in" a system by simply specifying its parameters. The above data of course presumes that the dish and feed are properly aligned: the effects of misalignment is discussed below. As was the case with horn antennas, for a given transmitter power, the larger the size of the dish the safer the equipment becomes, despite the fact that the effective radiated power is increased.

The hazard associated with the feed. It was shown in the previous section that provided the power supplied to a parabolic reflector was related in the way described to its diameter, then the radiation density could be held to a

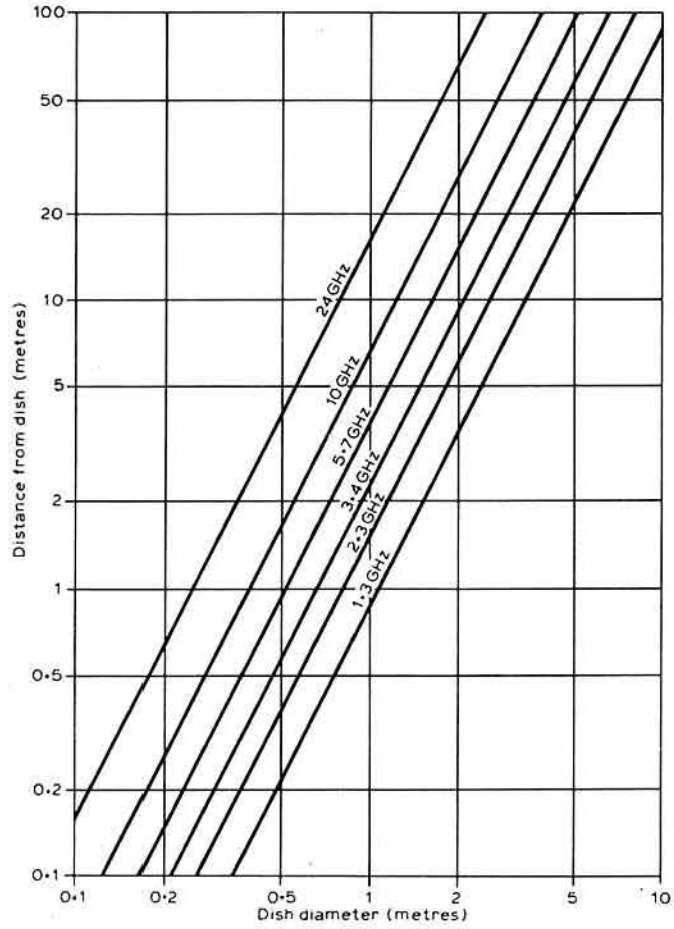

Fig 3. Distance from dish to point of maximum rf density as a function of frequency and dish size

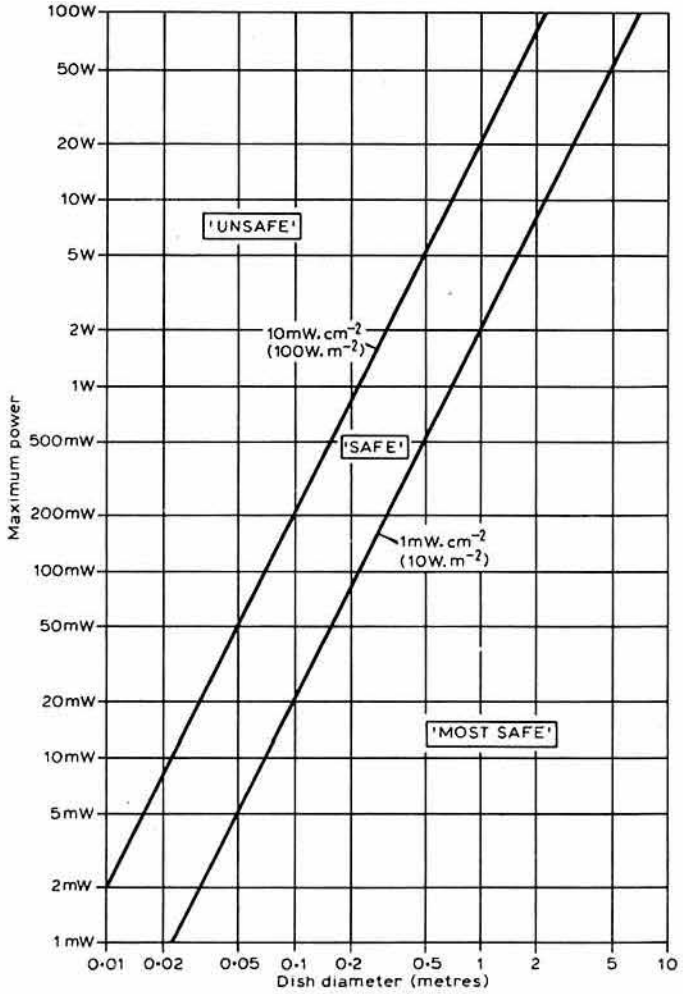

Fig 4. Maximum power to be fed to a dish so as not to exceed an rf density of 1 or 10mW/cm²

safe level anywhere outside the antenna. This could be achieved in practice without placing too restrictive limitations on the equipment design. For example, Fig 4 shows that the minimum size of dish to be used with a 2W transmitter should be 1m diameter if the radiation density external to the antenna structure is not to exceed 1mW/cm², or 20W if not to exceed 10mW/cm².

However, as the effective aperture of the feed supplying this power to the dish is usually much smaller than that of the dish, the radiation density associated with the feed will usually be at an unsafe level, and frequently at a hazardous level. The situation is somewhat similar to the horn antenna described earlier except that with a horn it is relatively difficult to physically reach the regions of high radiation density, whereas with a dish it is normally all too easy if the antenna is near ground level or not otherwise protected. The actual power density between the feed and the reflector will be set by the power of the transmitter and the dimensions of the feed. One of the simplest cases is that of the direct horn feed, in which the horn is mounted at the focus of the dish with its aperture directed at the dish. The actual dimensions of the feed depend on the frequency of operation and the ratio of the focal length of the paraboloidal reflector to its diameter, in the manner described in [2]. If it is assumed that access to the inside of the horn feed is prevented, then the maximum power that can be applied to the feed so as not to exceed a radiation density of 10mW/cm² as a function of the focal length/diameter (f/D) ratio of the dish and of frequency. These levels should be adopted if the system is to be operated at ground level for alignment.

Practical transmitters will normally generate significantly greater powers than those shown in Table 2. For a 1W transmitter at 10GHz, for example, the peak radiation density in front of a feed will be in the range of a few hundred milliwatts to a few watts per square centimetre depending on the f/D ratio of the dish. These levels are clearly unsafe, and it therefore makes good sense to operate the antenna in such a way as ensures that the operator and others cannot have access to that region of the antenna.

A popular second type of feed is the Cassegrain system, in which a horn

Table 2. Maximum power to be fed to a pyramidal horn feed as a function of f/D ratio for peak density not to exceed 10mW/cm²

Frequency (GHz)	Maximum power (mW) f/D = 0·25	f/D = 0·6	f/D = 1·0
1·3	370	1400	4500
2·3	120	440	1400
3·4	60	200	660
5·7	25	70	230
10	6	20	70
24	1	4	13

feed mounted through the centre of the dish radiates a sub-reflector which in turn illuminates the main reflector. With this system the main risk would seem to be spillage of rf around the edges of the sub-reflector. If this is to be limited to 10mW/cm², and the feed has a normal taper, in illumination of 10dB, then the radiation density at the centre of the sub-reflector must not exceed 100mW/cm². This is achieved if the power supplied to the antenna does not exceed 25AmW, where A is the area of the *sub-reflector* in square centimetres.

Calculations of radiation density around dipole-reflector combinations are difficult. There seems little doubt that stray radiation is likely to be at a somewhat higher level than with horn feeds, and therefore correspondingly greater precautions should be taken with this type of feed.

The effect of deficiencies in the antenna system

It is appropriate to refer briefly to a number of deficiencies in antenna systems which in some cases may lead to unexpected problems.

(a) Under-illumination of dish
In defining the maximum radiation density by the relationship 4P/A, the area A corresponds to the physical area of the reflector *assuming ideal illumination*. The use of a feed of too high a gain will result in under-illumination of the reflector so that its effective area is smaller than the physical area. This will lead to a higher power density close to the dish than would otherwise be expected.

(b) Over-illumination of dish
If the gain of the feed is too low, then an excessive amount of energy will spill over the edge of the dish. This will not be hazardous unless the power fed to the dish greatly exceeds the recommended value, as the density is normally designed to fall by typically 10dB between the centre and edge of the dish.

(c) Feed positioned inside the focus
If the feed is placed between the focus and the dish, the reflected beam will be divergent. As this will reduce the power density, this condition is relatively safe.

(d) Feed positioned beyond the focus
This is a potentially dangerous case because the reflected beam will tend to converge to a point some distance in front of the dish, with the risk that local power densities will approach those at the feed.

Rod array antennas

This case deserves to be considered as a separate situation. In general terms the stray radiation from this form of antenna would be expected to be greater than either horn antennas, or horn-fed dishes, and therefore greater precautions should be taken. It seems probable that the radiation pattern at a distance will be similar to that of a parabolic antenna of similar gain, and therefore the present design information will be relevant.

Other precautions

With high-power equipment it should be recognized that there are a number of other sources of hazards. For example, the leakage of rf from loosely-coupled connectors and waveguide flanges or the coupled output from a directional coupler may be at a sufficiently high level to represent a risk. In some cases, the power *reflected* from some surfaces may be at an unsafe level. It is obviously wise to recognize these possibilities and to adopt the same high standards of discipline for rf as amateurs obviously already do with other hazards such as high voltages.

References

[1] "RF hazards and the radio amateur", R. P. Blackwell, G8IZV, and I. F. White, G3SEK. *Rad Com* February 1982.

[2] *VHF/UHF Manual*, D. S. Evans, G3RPE, and G. R. Jessop, G6JP. RSGB.